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DAYLIGHTING AND ENERGY ANALYSIS FOR AIR-CONDITIONED OFFICE BUILDINGS

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Abstract—We propose a simple method for estimating the likely energy savings in electric lighting due to daylighting and the possible cooling penalty. Fractions of the working year and cooling season when daylighting alone is adequate to provide the indoor design illuminance are presented for on-off and top-up controls. Based on the simple average daylight factor method, energy savings in electric lighting have been estimated for a generic office building using measured outdoor illuminance data in Hong Kong. The daylight-induced cooling penalty is estimated using average solar heat gain factors. Our case study suggests that daylighting schemes can result in substantial energy savings in air-conditioned office buildings in Hong Kong. © 1998 Elsevier Science Ltd. All rights reserved

1. INTRODUCTION

People have become more conscious of the interactions between buildings, energy and the environment. There is a growing concern about energy consumption in buildings and its likely adverse effects on the environment. Hong Kong has seen marked increase in the energy use, particularly during the eighties [1]. Electricity use in the commercial sector increased at an average rate of 10% during the 25-year period, rising from 1,673 GWh in 1970 to 15,975 GWh in 1994. Lighting is one of the major electricity consuming items, particularly in commercial buildings. A recent study in Hong Kong has shown that electric lighting in office buildings accounts for 20–30% of total building electricity consumption, and it is believed that this is a potential area for energy savings in buildings [2].

In recent years, there has been increasing interest in incorporating daylight in the architectural and building designs to save energy in buildings. Proper lighting controls integrated with daylighting is recognised as an important and useful strategy in terms of energy-efficient building designs. Daylight does not require electricity and its high luminous efficacy provides the same illuminance level with less amount of heat generated. Energy savings from daylighting will result in not only low electric lighting and reduced peak electrical demands, but also reduced cooling loads and potential for smaller air-conditioning equipment size.

The principle of daylighting design is to maximize the utilization of available outdoor illuminance without imposing excessive cooling loads or causing glare. There exist some simple and very useful expressions for estimation of energy savings from different types of photo-electric lighting controls [3–5]. Attempts have also been made to consider the trade-off between daylight-induced energy savings and extra heating requirements due to bigger glazing areas and hence larger heat losses [6]. The interactions and relationships between lighting, heating and, especially, cooling, as well as their implications for energy consumption in buildings are complex. Building-energy simulation computer programs (e.g., DOE-2 [7]) are valuable design and analysis tools for assessing the energy performance of the building envelope savings and cooling energy requirements [8]. However, discussions with local architects and engineers have revealed that most designers would prefer a much simpler method to the rather complicated and time-consuming approach using hour-by-hour computation simulation tools, particularly during the initial design stage when several building schemes and concepts are being considered. Details of the window and lighting layout are usually not available at the early design stage.

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The aim of the present work is to develop a simple model which can be readily used by designers to consider the trade-off between daylight-induced savings in electric lighting and the daylight-induced cooling penalty by considering the average solar heat gain factors and the cumulative frequency distribution of the measured outdoor illuminance data. This would enable architects and engineers to compare the relative energy performance of different design schemes (e.g. window size and glazing type) during the initial design stage. Hourly data of global and diffuse solar radiation and outdoor illuminance on the horizontal surface have been measured on the roof top of the City University of Hong Kong since 1991 [9,10]. This paper describes the analysis of the daylight availability and the solar radiation data related to building designs in Hong Kong, and presents the development work on the simple energy savings estimation model using these data.

2. SOLAR HEAT GAIN FACTORS

It has been shown that solar heat gain factors (SHGFs) in W/m^2 for the horizontal and vertical surfaces may be expressed as follows [11]:

$$\text{SHGF} = I_{bh}(\tau_b + 0.267\alpha_b) + 0.8135 I_{dh} \text{ for horizontal surfaces,} \tag{1}$$

$$\text{SHGF} = I_{bv}(\tau_b + 0.267\alpha_b) + 0.8135 I_{dv} \text{ for vertical surfaces,} \tag{2}$$

where I_{bh} = direct beam radiation on the horizontal surfaces (W/m^2), τ_b = transmittance of the reference glazing for the direct beam radiation, α_b = absorptance of the reference glazing for the direct beam radiation, I_{dh} = diffuse radiation on the horizontal surface (W/m^2), I_{bv} = direct beam radiation on the vertical surface (W/m^2), I_{dv} = diffuse radiation on the vertical surface (W/m^2).

Vertical data (i.e. I_{bv} and I_{dv}) were determined from the measured horizontal data (i.e. I_{bh}, I_{dh} and the horizontal global radiation I_{gh}) as follows:

$$I_{bv} = (I_{bh}/\sin\alpha) \times \cos\theta, \tag{3}$$

$$I_{dv} = 0.5 I_{dh} + 0.5\rho I_{gh}, \tag{4}$$

where α, θ and ρ are the solar altitude, angle of incidence and ground reflectivity, respectively. Equation (4) is approximate and only valid for unobstructed horizontal surface. It has diffuse and reflected components. The first term involves the assumption that the vertical window receives half as much diffuse radiation as the horizontal surface and the second term that the vertical surface receives half of the total solar radiation reflected from the ground. A common ground reflectivity value of 0.2 was used.

Transmittance and absorptance for direct radiation are a function of the incident angle of the solar beam relative to the surface. A fifth-order polynomials expressing these properties in terms of the angle of incidence was adopted [12]. For the ASHRAE reference glazing, transmittance and absorptance are determined from

$$\tau_b = -0.00885 + 2.71235\cos\theta - 0.62062\cos^2\theta - 7.07329\cos^3\theta + 9.75995\cos^4\theta - 3.89922\cos^5\theta, \tag{5}$$

$$\alpha_b = 0.001154 + 0.77674\cos\theta - 3.94657\cos^2\theta + 8.57881\cos^3\theta - 8.38135\cos^4\theta + 3.01188\cos^5\theta. \tag{6}$$

Equations (1) and (2) were used to determine the hourly SHGFs (for every daylight hour throughout the year) for the horizontal surface and the eight principle vertical orientations (i.e. N, NE, E, SE, S, SW, W, NW), respectively. Average hourly SHGFs were calculated for the six-month cooling season (May–October), the nine-month cooling season (March–November) and the whole year, i.e.

$$\text{Average SHGF} = [\sum_{j=1}^{N}(\sum_{i=1}^{n}\text{SHGF}_{ij})]/(24 \times N), \tag{7}$$

where n = number of daylight hours per day, N = number of days in the averaging period. The six-month and the nine-month cooling seasons are recommended for the estimating of the total solar heat gain for residential and commercial buildings, respectively. Fig. 1 shows the electricity consumption profiles for the residential and commercial sectors in Hong Kong in 1994 [13]. Electricity demands in the residential sector start picking up in May and fall off in October; the increase is mainly due to air-conditioning. For the commercial sector, the cooling season is longer, from mid-March to mid-November. This is because of the higher internal loads such as people, lighting and office equipment.

The total solar heat gain within a certain period for any surface is

$$Q = \text{Average SHGF} \times A_w \times SC \times H/1000, \tag{8}$$

where Q = solar heat gain (kWh), A_w = window area (m^2), SC = glass shading coefficient, $H = 24 \times N$ = total number of hours.

Table 1 summarises the average hourly SHGFs for the eight orientations and the horizontal surface. The average SHGFs range from 37.8 W/m^2 for the north-facing surface for the whole year to 146.2 W/m^2 for the horizontal surface for the six-month cooling season. Low SHGFs indicate diffuse radiation is the major component of the solar radiation received, while high SHGFs show that solar heat gain is mainly due to direct radiation. SHGFs for the east-facing and west-facing surfaces are almost symmetrical, with the latter being slightly higher. For office buildings with a 51/2-day working week, Q in Eq. (8) should be multiplied by a factor of 5.5/7.

3. DAYLIGHT AVAILABILITY AND ENERGY SAVINGS

For daylighting design and calculations, the cumulative frequency distribution of outdoor illuminance can indicate the percentage of the working year in which a given illuminance is exceeded. This is

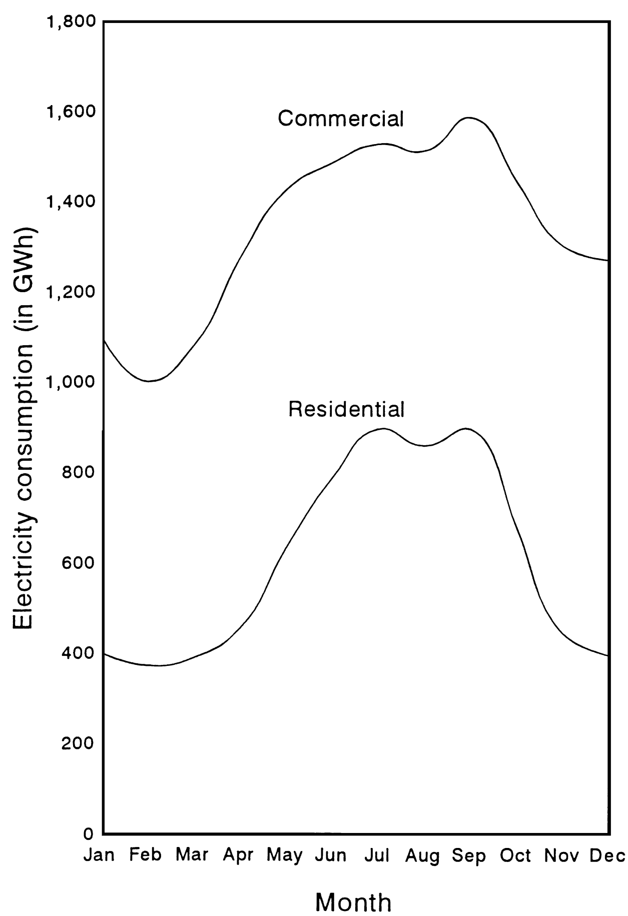

Fig. 1. Monthly electricity consumption profiles for the residential and commercial sectors in 1994.

Table 1. Average hourly solar heat gain factors for Hong Kong

	Average SHGF (W/m^2)									Total no. of Hours
Period	N	NE	E	SE	S	SW	W	NW	Hor.	
6-month cooling season	44.8	59.7	74.7	72	62.9	71.2	74.7	60.5	146.2	4416
9-month cooling season	41.1	53.1	68.3	69.7	64.8	69.6	69	54.2	133.2	5880
Annual	37.8	47.8	63.5	69.1	68.8	69.7	64.6	48.6	123	8760

useful for determining the necessary use of artificial lighting, and the probable energy savings from on-off controls. If we do not take into account the differential switching or dead band, then, to a good approximation, the fraction of the working year that electric lighting would be off under an on-off control is simply given by the fraction of the working year that the daylight threshold illuminance level is exceeded. Cumulative frequency distribution for the measured E_g was calculated and is shown in Fig. 2. The distribution is based on typical office hours of 08:00–18:00 in Hong Kong. It can be seen that for 60% of the working year, the outdoor global illuminance exceeds 25 klux. This implies that if an office has a daylighting design with an average daylight factor of 2% (based on the prevailing average sky conditions, not the overcast sky) and the required indoor design illuminance is 500 lux, then for 60% of the time, daylighting alone can provide adequate illumination in that office. This assumes single-zone control and ignores non-uniformity of daylight levels within the interior. In reality, the percentage would be different depending on the types of zonal control [14].

For daylighting applications, diffuse illuminance is more important and widely used. The use of the direct sunlight for providing daylight in buildings has often been excluded in general daylighting designs. Problems of glare, excessive brightness ratios and thermal discomfort have supported the exclusion. Also, diffuse illuminance in daylighting design is considered more energy-efficient because of higher luminous efficacy [9]. The cumulative frequency distribution of the diffuse component is also shown in Fig. 2. The maximum illuminance is 60klux, about half of the maximum E_g. If blinds or other shading devices are used to exclude direct sunlight and admit only diffuse daylight, about 40% of the time of the working year daylighting alone would be adequate to provide a 500 lux indoor illuminance with an average 2% daylight factor.

Broadly speaking, there are two basic categories of lighting controls, namely on-off and top-up (dimming). An on-off control is designed to switch artificial lighting on and off automatically as the daylight level falls and rises, respectively through a predetermined level. Top-up controls vary the light output of lamps in accordance with the prevailing daylight level. When daylight is inadequate to achieve the required design illuminance, the indoor lighting level is topped up by artificial lighting. The fractional saving from a top-up control is equal to the fractional saving using an on-off control plus the extra fractional saving using a dimming system to top-up. Assuming 12% of total electric lighting energy is consumed by the control gear [4], the fraction of the working year when daylighting is adequate for a top-up control becomes

$$F_t = F_o + 0.88(I_d/E_o), \tag{9}$$

where F_t = fraction of the working year when daylighting alone can achieve the required indoor design illuminance using a top-up control, F_o = fraction of the working year when daylighting alone can achieve the required indoor design illuminance using an on-off control, I_d = summation of the products of frequency f and its corresponding illuminance in mid-point of each 1klux interval up to E_o, E_o = required outdoor illuminance which will provide adequate indoor illuminance.

To assess the potential energy savings due to daylighting, percentages of the working year when daylighting can provide adequate illuminance for different daylight factors were calculated and are shown in Figs 3 and 4 for the on-off and the top-up controls, respectively. Daylight factor is defined as the ratio of the indoor horizontal illuminance to the measured horizontal outdoor illuminance under

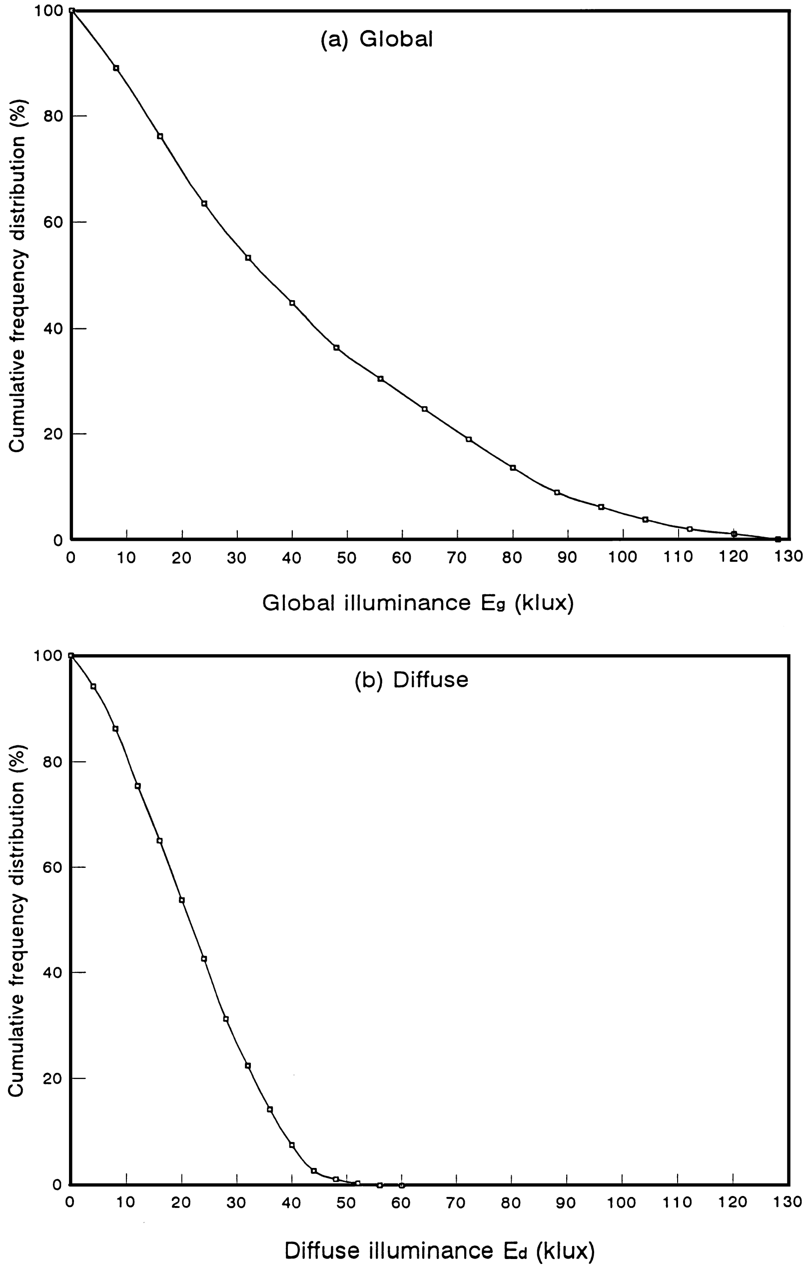

Fig. 2. Cumulative frequency distributions for measured outdoor global and diffuse illuminance.

real sky conditions (not overcast sky), and is assumed to be constant. Strictly speaking, daylight factor as defined will vary, depending on the position of the sun, the actual sky conditions and the orientations of the fenestration [15,16]. However, it is believed that Figs 3 and 4 can give a good indication of the overall trend of how lighting energy savings would vary with different daylight factors and indoor design illuminances. This is because although the absolute magnitude would change, the relative increase or decrease in energy savings and the overall trend would not differ significantly. Calculations were based on the cumulative frequency distribution for the measured outdoor global illuminance shown in Fig. 2(a). It can be seen that both on-off and top-up controls enjoy high energy savings at low indoor design illuminances and large daylight factors. For high indoor design illuminance, top-up controls are much more effective than on-off controls. The various graphs also show diminishing return for an illuminance of 500 lux or less with a daylight factor of 5% or more.

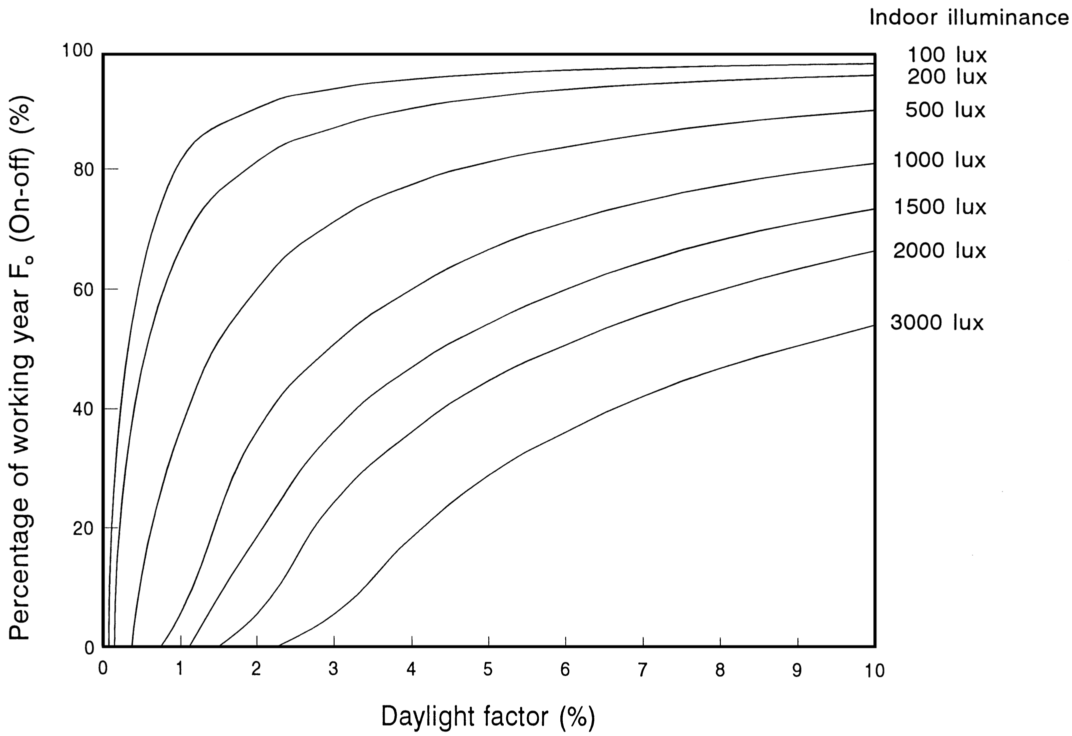

Fig. 3. Percentage of working year when daylighting alone can achieve the required indoor design illuminance using on-off control.

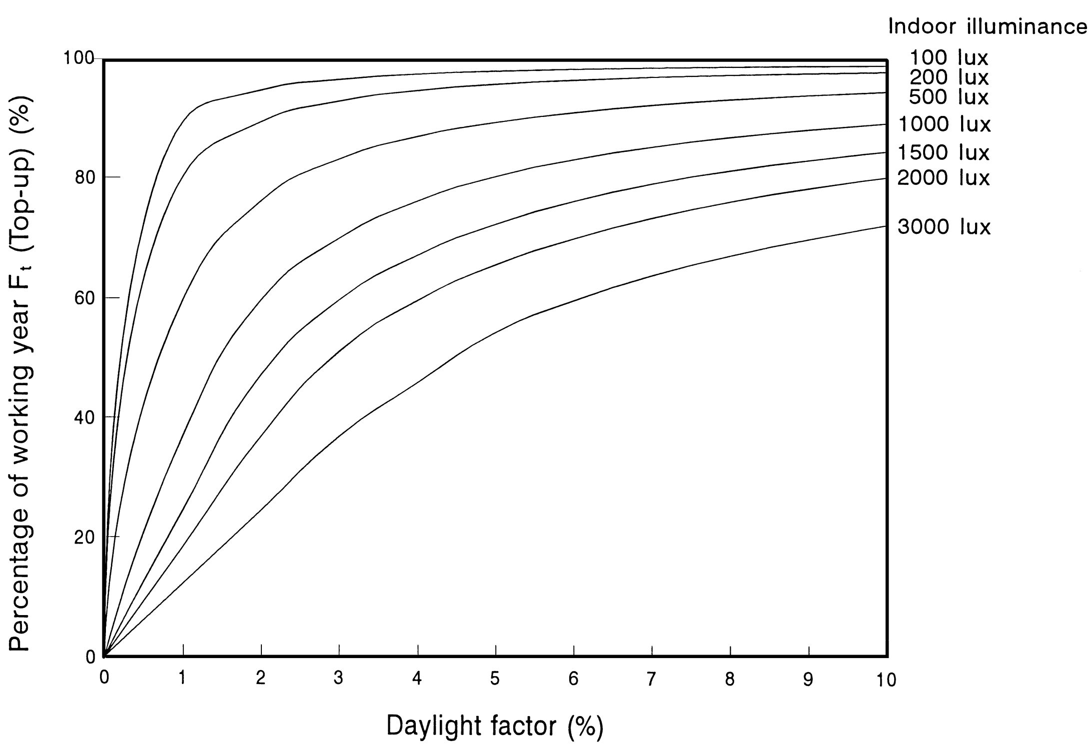

Fig. 4. Percentage of working year when daylighting alone can achieve the required indoor design illuminance using top-up control.

4. DAYLIGHT ENERGY SAVINGS AND COOLING PENALTY

Energy savings in electric lighting per year are given by

$$E_a = LPD \times A_f \times H_a \times F/1000, \tag{10}$$

where E_a = annual energy savings in electric lighting (kWh), LPD = installed lighting power density (W/m^2), A_f = floor area (m^2), H_a = annual operating hours of the electric lighting system (hour), $F = F_o$ (for on-off control), $F = F_t$ (for top-up control).

For fully air-conditioned office buildings, cooling requirements are affected by the solar heat gain through the windows as well as the sensible heat gain from the electric lighting system into the air-conditioned space. Assuming all the electrical power consumed by artificial lighting eventually turns into sensible heat within the air-conditioned space, then the reduction in cooling requirement will be equal to the energy savings in electric lighting for a daylit air-conditioned office space. Consequently, the daylight-induced cooling benefit or penalty is simply given by the difference between the amount of solar heat gain through the windows and the amount of electric lighting energy savings.

As mentioned earlier, air-conditioned office buildings in Hong Kong tend to have cooling requirements during the nine-month period from March to November. Total solar heat gain through the windows during the nine-month period is given by Eq. (8), with the average SHGF and the averaging period correspond to the nine-month cooling season. Electric lighting energy savings during the cooling season are as follows:

$$E_c = LPD \times A_f \times H_c \times F_c/1000, \tag{11}$$

where E_c = electric lighting energy savings during the cooling season (kWh), H_c = total hours of operation of electric lighting during the cooling season (hour), F_c = fraction of the working cooling season when daylighting alone can achieve the required indoor design illuminance = F_{oc} (for on-off control), $F_c = F_{tc}$ (for top-up control). Values of F_{oc} and F_{tc} were calculated for different daylight factors and indoor design illuminances. These are shown in Figs 5 and 6. Trends and features of Figs 5 and 6 are very similar to those shown in Figs 3 and 4 for the whole year.

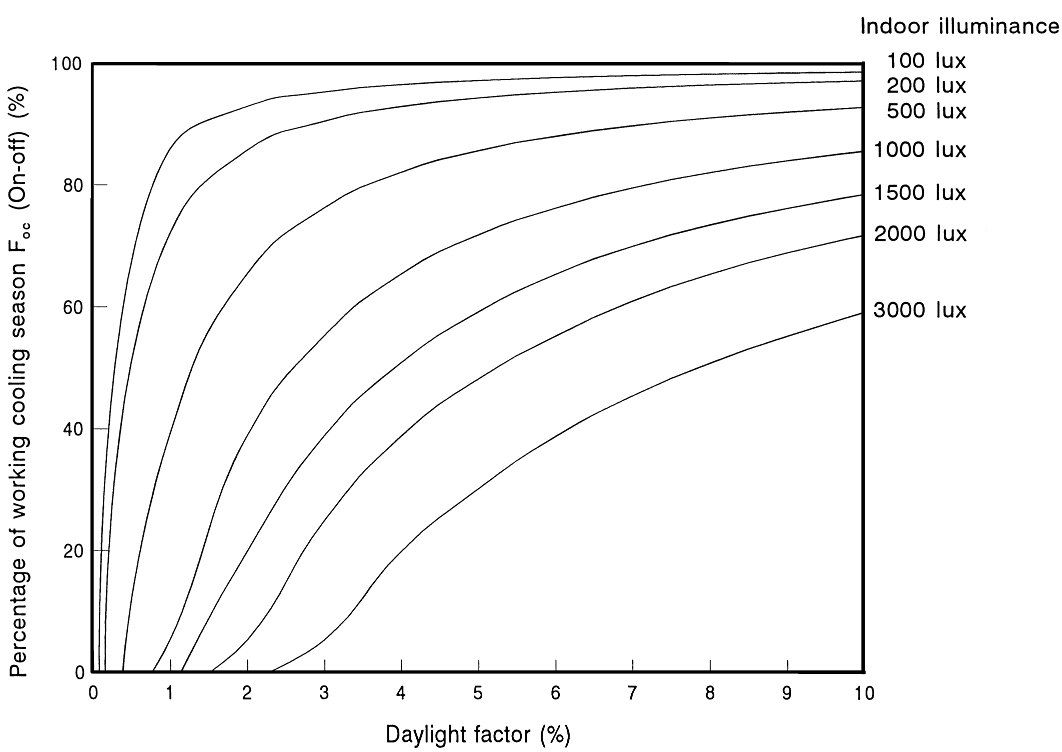

Fig. 5. Percentage of working cooling season when daylighting alone can achieve the required indoor design illuminance using on-off control.

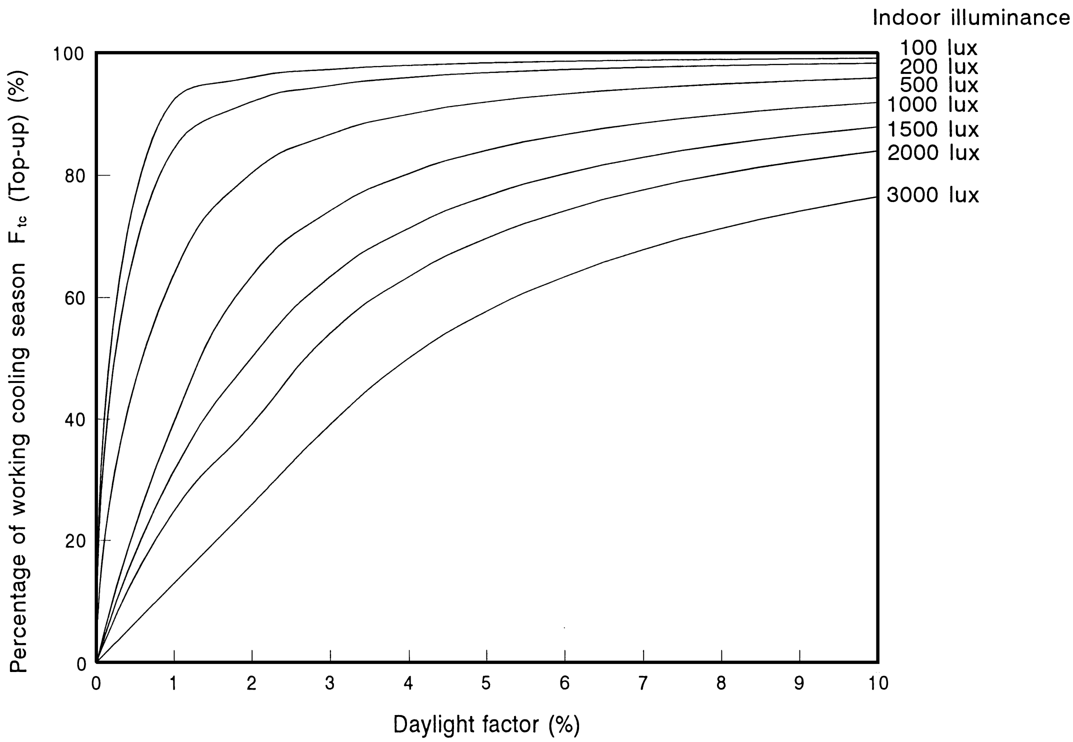

Fig. 6. Percentage of working cooling season when daylighting alone can achieve the required indoor design illuminance using top-up control.

5. EXAMPLES

The application of this simple estimation method can best be illustrated with case studies. This can also give us a feel for the likely magnitude of energy savings when using daylighting schemes in Hong Kong. The case studies are based on a generic 40-storey office building with curtain walling design using reflective glass. The generic building is based on a survey of commercial buildings in Hong Kong [17]. It is 35 m × 35 m with four 4.5 m-deep perimeter zones. Only the perimeter zones were considered in the case study with the following assumptions: (i) reflective glass, $SC = 0.4$ and light transmittance (LT) = 0.3, (ii) window-to-wall ratio (WWR) = 44%, floor-to-floor height = 3.4 m, (iii) indoor design illuminance = 500 lux, $LPD = 20\ \mathrm{W/m^2}$, (iv) a 10-hour working day (08:00–18:00) and a 51/2-day working week, (v) no external obstruction.

Crisp and Littlefair [18] have developed a simple average daylight factor method as a design criterion, which enables the designer to get a feel for the window area required to achieve a certain indoor daylighting level at the initial design stage. Thus,

$$DF = (A_w \times LT \times V)/[(A_{int} \times (1 - R^2)], \tag{12}$$

where DF = average daylight factor of all the internal surfaces, A_w = window area (m^2), V = vertical angle subtended by the sky at the centre of the window (degrees), A_{int} = total area of the internal surfaces (m^2), R = area-weighted mean reflectance of the internal surfaces (assumed to be 0.5 in the present study).

Equation (12) was used in the present study to estimate the daylight factor for the perimeter zones of the generic office building. Calculations were based on the data outlined above. At the initial design stage, detailed daylighting distributions within an office space are usually not required. This simple daylight factor method allows the designer to get some idea about the relationship between the various window system design parameters such as glass type and area, and the likely daylight factor. The average daylight factor was found to be about 4.5%. This was assumed to be the average daylight factor of the working plane. Since the aim is to compare the relative energy performance of different conceptual design schemes, this approximation is considered acceptable. Equation (10) was used to

Table 2. Estimated annual electricity savings/penalty for on-off controls (kWh/m^2)

Observed changes	North	East	South	West	Mean
(a) Increase in solar heat gain	0.0	0.0	0.0	0.0	0.0
(b) Reduction in sensible heat gain from artificial lights	31.1	32.5	32.4	33.1	32.3
(c) Electricity savings/penalty in cooling[a], [(b) − (a)] ÷ 3[b]	10.4	10.8	10.8	11.0	10.8
(d) Electricity savings in artificial lighting	43.6	46.2	47.5	47.3	46.2
(e) Overall electricity savings/penalty[a], (c) + (d)	54.0	57.0	58.3	58.3	56.9

[a]Negative values indicate a penalty; [b]we assume a coefficient of performance of 3 for the chiller plants.

estimate the annual energy savings in electric lighting. The fractions of the working year when daylighting is adequate (i.e. F_t and F_o) were obtained from Figs 3 and 4 with a 4.5% daylight factor and a 500 lux indoor design illuminance. To cater for the effects of orientation on the daylighting level, the approach using the total orientation factor formula developed by Littlefair [19] was used to determine the orientation factors. The orientation factors for north, east, south and west are 0.92, 1.12, 1.33 and 1.32, respectively. These values were used in the calculation of F_t and F_o for the four orientations. Equations (8) and (11) were used to calculate the solar heat gain and the reduction in sensible heat from electric lighting during the nine-month cooling season.

Three cases were considered. Case I refers to comparisons of two designs, one with daylighting controls and the other without. Tables 2 and 3 show the estimated energy savings for using the on-off and top-up controls, respectively. It can be seen that the estimated energy savings are quite substantial. Table 2 indicates that electricity savings for artificial lighting ranges from 43.6 kWh/m^2 for the north perimeter zone to 47.5 kWh/m^2 for the south perimeter office. The overall effect of incorporating daylighting is the reduction of electric energy use of 56.9 kWh/m^2 per year for the perimeter zones. Similar features are observed for the top-up controls shown in Table 3. These figures, however, should only be regarded as an indication of the likely magnitude of energy savings. In Hong Kong, most commercial development projects are close to each other and hence external obstructions can be severe. It is therefore envisaged the energy savings will be less than those shown in Tables 2 and 3. Nevertheless, it is believed that energy savings can still be significant.

Table 3. Estimated annual electricity savings/penalty for top-up controls (kWh/m^2)

Observed changes	North	East	South	West	Mean
(a) Increase in solar heat gain	0.0	0.0	0.0	0.0	0.0
(b) Reduction in sensible heat gain from artificial lights	34.3	35.1	35.0	35.5	35.0
(c) Electricity savings/penalty in cooling[a], [(b) − (a)] ÷ 3[b]	11.4	11.7	11.7	11.8	11.7
(d) Electricity savings in artificial lighting	49.4	51.0	51.8	51.6	50.9
(e) Overall electricity savings/penalty[a], (c) + (d)	60.8	62.7	63.5	63.4	62.6

[a]Negative values indicate a penalty; [b]we assume a coefficient of performance of 3 for the chiller plants.

Table 4. Estimated annual electricity savings/penalty for larger window area (kWh/m²)

Observed changes	North	East	South	West	Mean
(a) Increase in solar heat gain	17.4	29.0	27.5	29.3	25.8
(b) Reduction in sensible heat gain from artificial lights	2.7	2.2	2.2	2.0	2.3
(c) Electricity savings/penalty in cooling[a], [(b) − (a)] ÷ 3[b]	− 4.9	− 8.9	− 8.4	− 9.1	− 7.8
(d) Electricity savings in artificial lighting	4.5	3.9	3.6	3.6	3.9
(e) Overall electricity savings/penalty[a], (c) + (d)	− 0.4	− 5.0	− 4.8	− 5.5	− 3.9

[a]Negative values indicate a penalty; [b]we assume a coefficient of performance of 3 for the chiller plants.

In Case II, we consider the effect of increasing the window size. Table 4 summarises the effects of changing the WWR from 44% to 70%. On-off controls were assumed for both designs. It can be seen that the increase in solar heat gain ranges from 17.4 kWh/m² for the north perimeter office to 29.3 kWh/m² for the west, with a mean value of 25.8 kWh/m². The larger window area provides more natural light and results in a slight reduction in the amount of sensible heat gain from the electric lighting system. The overall effect is an increase of 3.9 kWh/m² for the perimeter zones. In Case III, we assess the consequence of using tinted glass with a shading coefficient of 0.7 and a light transmittance of 0.5, instead of the reflective glass considered in cases I and II. Again, on-off controls were assumed. Table 5 shows the findings. A higher light transmittance allows more daylight and hence less electricity consumption for artificial lighting and bigger reduction in sensible heat gain from electric lights compared with the reflective glass. However, tinted glass admits more solar heat and the overall effect is an increase of electricity use of 5.8 kWh/m² per year for the perimeter offices.

6. CONCLUSIONS

In subtropical Hong Kong, about 40–60% of the time, indoor illuminance can be provided by daylight for office space with a 2% daylight factor design. Using the measured data, sets of curves to predict electric energy savings under on-off and top-up controls have been presented. These simple curves are useful for assessing different daylighting schemes during the initial design stage. A simple method for

Table 5. Estimated annual electricity savings/penalty for using tinted glass instead of reflective glass (kWh/m²)

Observed changes	North	East	South	West	Mean
(a) Increase in solar heat gain	21.8	36.2	34.4	36.6	32.2
(b) Reduction in sensible heat gain from artificial lights	2.8	2.3	2.4	2.2	2.4
(c) Electricity savings/penalty in cooling[a], [(b) − (a)] ÷ 3[b]	− 6.3	− 11.3	− 10.7	− 11.5	− 10.0
(d) Electricity savings in artificial lighting	4.8	4.2	3.8	3.9	4.2
(e) Overall electricity savings/penalty[a], (c) + (d)	− 1.5	− 7.1	− 6.9	− 7.6	− 5.8

[a]Negative values indicate a penalty; [b]we assume a coefficient of performance of 3 for the chiller plants.

estimating daylight-induced cooling penalty using average solar heat gain factors has been proposed. A case study based on a generic reference office building indicates that energy savings in electric lighting can be in the order of 40–50 kWh/m^2 per year for the perimeter zones if daylighting schemes using on-off or top-up controls are incorporated in the architectural and building design. Case studies were also conducted to assess the effects of changing the window area and the glass type.

It is hoped that the method presented can help architects and building engineers assess the relative energy performance of different design schemes and estimate the likely energy benefits or penalty during the initial design stage. Although the work presented is based on the Hong Kong environment, it is believed that the methodology and procedures outlined can be applied to other cooling dominated buildings, particularly in the tropical and subtropical regions. Local data for the external illuminance and the solar heat gain factors would have to be measured and developed though. This may have great energy implications for the fast building development programmes being implemented in the special economic regions in southern China.

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